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MULTIDISCIPLINARY COMPUTATIONAL RESEARCH

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14. ABSTRACT

The purpose of this work is to develop advanced multidisciplinary numerical simulation capabilities for aerospace vehicles with emphasis on highly accurate, massively parallel computational methods for Direct and Large-Eddy simulation of turbulence, flow control, aero-acoustics and nonlinear fluid/structure interactions. These technical objectives directly support AFRL Air Vehicles Directorate's Capability Focused Tech Investment in persistent ISR, Strike and Multi-Role Mobility thrusts.

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Computational fluid dynamics, multidisciplinary computations, higher-order methods, direct numerical simulation, large-eddy simulations, aero-acoustics, fluid-structure interactions

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MULTIDISCIPLINARY COMPUTATIONAL RESEARCH

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Objectives

To develop advanced multidisciplinary numerical simulation capabilities for aerospace vehicles with emphasis on highly accurate, massively parallel computational methods for Direct and Large-Eddy simulation of turbulence, flow control, aero-acoustics and nonlinear fluid/structure interactions. These technical objectives directly support AFRL Air Vehicles Directorate's Capability Focused Tech Investment in persistent ISR, Strike and Multi-Role Mobility thrusts.

Progress

During this reporting period, significant progress has been achieved in several research areas pertinent to the present task. These include: (i) flow control of external and internal flows employing plasma actuators, (ii) development and validation of a hybrid high-order RANS/ILES technique, (iii) investigation of the flow structure over non-slender delta wings and a generic UCAV configuration, and (iv) non-linear fluid-structure interactions on a highly flexible wing. Only some research highlights for plasma-based flow control are included in this summary.

Control of Transitional and Turbulent Flows Using Plasma-Based Actuators

Control of separated flows using simulated plasma (DBD) actuators was investigated. Since the flows are typically characterized by transition and turbulence, a high-fidelity three-dimensional viscous methodology is required. This high-end simulation technique is computationally intensive, and therefore, a first-principles fully-coupled approach of the plasma effects, even if available, becomes prohibitive. For this reason, at this stage, the plasma-induced body forces are represented using either a phenomenological model [1] or a loosely-coupled first-principles approach [2]. These methods represent respectively the averaged and instantaneous force introduced by the actuator in a specified plasma region above the device. Strategies for the effective control of separation were explored. Emphasis was placed on the greater importance of unsteady forcing rather than pure streamwise momentum injection as the primary control mechanism. With the exception of very low freestream velocities or very strong wall jet effects, transition/turbulence enhancements are found to be the dominant mechanism. The present emphasis also dictates the use of a high-fidelity three-dimensional computational approach capable of describing the impact of unsteady forcing on the spatio-temporal transition/turbulence structure. A comprehensive set of applications was considered, including suppression of wing stall, control of boundary layer transition on a plate, control of vortex breakdown over a delta wing, control of laminar separation over a ramp, and turbulent separation over a wall-mounted hump.

Control of Wing Stall

Control of the stalled flow past a NACA 0015 airfoil section was investigated [1]. The Mach number, chord Reynolds number and angle of attack were chosen as $M = 0.1$, $Re_c = 45{,}000$ and $\alpha = 15^o$, respectively. This particular case was previously considered in Ref. [2]. However, in the present work, both pulsed co-flow and counter-flow actuators are used, and much smaller plasma

forces are prescribed in order to demonstrate control effectiveness by promoting transition and turbulence. The actuator origin was located at x/c = 0.024, just downstream of the mean boundary-layer separation point for the baseline flow. The geometric parameters of the simulated plasma region, as well as the corresponding actuator strength (D_c), orientation and duty-cycle primary frequency are provided in Ref. [1].

The global structure of the baseline and controlled flow fields is shown in Fig. 1 in terms of streamwise velocity and spanwise vorticity contours. At this high incidence, the baseline flow is observed to be fully stalled. The time-averaged velocity contours (Fig. 1b) display a separation zone which extends significantly in the direction normal to the wing section. Control of the stalled airfoil flow was investigated employing both steady and pulsed, as well as co-flow and counter-flow DBD actuators.

The use of a steady (i.e. continuous) co-flow actuator was first considered. Examination of the transient response of the flow following the onset of actuation indicated that, initially, a significant downstream displacement of the separation point takes place due to the actuator-induced streamwise wall jet. However, despite this beneficial transient effect, the flow eventually returns to a completely stalled condition (Figs. 1a,b). Comparison of the C_p-distributions and velocity profiles near midchord (x/c = 0.42) shows no significant improvement with control (Fig. 2). Therefore, steady actuation (modeled with the phenomenological approach) is found to be ineffective for the actuator strength parameters considered. It should be noted that for a value of D_c an order-of-magnitude larger, the simulated steady actuator was previously found [2] to fully attach the flow due to the formation of a very strong wall jet. The present results suggest that a steady actuator force of limited magnitude is not an effective means of flow control, and attempts to attach the boundary layer through pure streamwise momentum injection are therefore of limited applicability.

In order to exploit the receptivity of the flow to unsteady disturbances, a pulsed co-flow actuator with a primary duty-cycle non-dimensional frequency St = fc/U = 4.0 was considered. As shown in Fig. 1, the pulsed actuation reattaches the separated flow. The mean surface pressure (Fig. 2) exhibits a well-defined suction peak, and the velocity profile near mid-chord displays a fully-attached character. Examination of the instantaneous vorticity contours (Fig. 1c) indicates that the pulsed force engenders a rapid transition to turbulence of the initially laminar shear layer.

In order to contrast the relative importance of transition and turbulence enhancement mechanisms relative to simple wall-jet momentum injection arguments, the impact of a counter-flow actuator was also explored. As shown in Fig. 1, a pulsed counter-flow actuator was found to be equally effective in eliminating stall. This control is again achieved by the rapid transition downstream of a small separation bubble generated by the counter-flow actuator. The pulsed counter-flow actuator was found to be even more effective when doubling the strength parameter, which further emphasizes the importance of unsteady forcing rather than momentum injection as the primary control mechanism.

The effect of pulsing frequency was also considered for the counter-flow actuator with a fixed strength parameter. A comparison of the instantaneous flow fields obtained with the lowest (St = 1.0) and highest (St = 8.0) pulsing frequencies is shown in Fig. 3. Although with St = 1.0 the flow

begins to transition downstream of the actuator, the process is not as effective as for the case of high-frequency pulsing. With St = 8.0, the shear layer quickly breakdowns due to spanwise instabilities, and much higher values of vorticity are observed near the wing surface. In each cycle of the pulsing, a dynamic-stall-like vortex is generated near the leading edge downstream of the actuator. For the higher frequency, this leading-edge vortex forms closer to the actuator and to the airfoil surface. The actuator-induced vortex is observed to be initially coherent but quickly breakdowns due to spanwise instabilities. It therefore appears that the increased control effectiveness of the pulsed actuator derives from the process of modulated vorticity injection. The time-averaged surface pressure and velocity profiles are displayed for all values of St in Fig. 4. The mean surface pressure exhibits the development of a stronger suction peak with increasing frequency, however this effect seems to saturate after St = 4.0. Comparison of the velocity profiles shows also a marked reduction of the boundary layer displacement with increasing St.

Finally, results computed with a loosely-coupled first-principles approach for a co-flow actuator showed that the high-frequency forcing (radio frequency) associated with continuous actuator operation promoted transition to turbulence [1]. For this case, the phenomenological approach, which assumes a time-invariant force, could not reproduce the transition/turbulence enhancements associated with the inherent unsteady forcing. Comparison of the results obtained with the first-principles high-frequency (monochromatic) forcing with the pulsed cases indicated that the duty cycle (with sufficiently high pulsing frequency) provided a significant improvement in control effectiveness. This is due to the fact that the flow is more receptive to the intermediate forcing frequencies rather that the extremely high radio frequency itself. Future computations with a duty cycle using the first-principles approach are required to validate this conclusion and to further assess the merits of the phenomenological model for the case of pulsed actuation.

<u>Control of Laminar Separation Over a Ramp</u>

Control of boundary-layer separation over a generic ramp configuration was also considered. This simple geometry is taken as a model problem of separation near the trailing edge of a natural laminar flow wing section. The flow conditions were Mach number M = 0.1 and Reynolds number $Re_c = 6.0 \times 10^4$ (based on ramp length). The incoming boundary layer was assumed to be laminar upstream of the ramp, with a nominal thickness $\delta/c= 0.0625$.

The baseline instantaneous and time-averaged flow field structure is shown in Figs.5 and 6, respectively. The incoming laminar boundary layer is observed to separate immediately upon encountering the ramp, and a large time-averaged re-circulation region is formed. Downstream of separation, a laminar free shear layer is formed which subsequently rolls up into coherent spanwise vortices and abruptly breakdowns just upstream of re-attachment. In order to control this massive separation region, we first considered a pulsed co-flow DBD actuator (St = 3.2) located just upstream of the ramp (x/c = -0.13). With the actuator on, the breakdown process of the shear layer is observed to move closer to the separation point due to the unsteady forcing. As a result of this turbulence enhancement, a significant reduction is achieved in the size of the mean separation region.

As was shown in our previous work [1, 3], a low-power counter-flow DBD actuator can be used as an effective on-demand boundary-layer tripping device. Therefore, we considered the use of this strategy for the control of laminar separation over the ramp. For this purpose, instead of employing

a co-flow pulsed actuator near the separated laminar shear layer, we use a steady counter-flow actuator to promote boundary-layer transition to turbulence upstream of the ramp. As observed in Fig. 5, the laminar boundary layer begins to transition downstream of the counter-flow actuator. This allows the flow to turns downward upon encountering the ramp without significant boundary-layer separation (Fig. 6). The flow is now practically re-attached, with the exception of a much smaller time-averaged separation bubble at the end of the ramp.

These exploratory results clearly demonstrate that for separated laminar flows, encountered in off-design operation of laminar flow wings and low-pressure turbines, improved control may be achieved through modification of the boundary layer sufficiently upstream of the adverse pressure gradient region. In this manner, suppression of massive separation can be obtained with a significant reduction in the actuator power requirements. This strategy may also provide scalability to higher freestream velocities encountered in practical applications. This approach is currently being used for separation control of a low-pressure turbine at low Reynolds number.

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3. Visbal, M. and Gaitonde, D., "Control of Vortical Flows Using Simulated Plasma Actuators," AIAA Paper 2006-0505, Jan. 2006.

Personnel Supported

Dr. Peter Attar (NRC)	Dr. Raymond Gordnier	Dr. Philip Morgan (OAI)
Dr. Donald Rizzetta	Dr. Scott Sherer	Dr. Miguel Visbal (Team Leader)

Honors/Awards, Professional Activities

Visbal, M., AIAA Applied Aerodynamics Best Paper Award (2006), Royal Aeronautical Society Silver Award and Busk Prize (2006);USAF Basic Research Award (2004); AFRL Fellow (1995); Outstanding Scientist of Dayton (2003); Gen. B. Foulois Award, Air Vehicles Directorate (1990,1999); NRC Mentor; Invited Speaker AIAA Aerospace Sciences Meeting (2006); AIAA Aero-acoustics Technical Committee; Co-organizer of LES/DNS, Algorithm Development and Fluid-Structure Interaction Symposia, ASME 2006 Summer Conference.
Gordnier, R., AFRL Fellow (2003); Gen. B. Foulois Award, Air Vehicles Directorate (1997); AIAA Structural Dynamics Technical Committee; NRC Mentor; Keynote Speaker, ASME 2006 Fluids Engineering Conference; Royal Aeronautical Society Silver Award and Busk Prize (2006).
Rizzetta, D., Gen. B. Foulois Award, Air Vehicles Directorate (2001); NRC Mentor; AIAA Fluid Dynamics Technical Committee.

Interactions / Transitions

C. Liu, Univ. of Texas at Arlington; high-order-methods, DNS
D. Hixon, Univ. of Toledo, high-order methods, aero-acoustics
V. Golubev, Embry-Riddle Univ.; gust-airfoil interactions

F. Laidende, SUNY; high-order methods, aero-acoustics
S. Lele, Stanford Univ.; high-order overset solver
R. Moser, Univ. of Illinois; LES
Gursul, Bath Univ., UK; vortical flows, flexible delta wings
P. Seshaiyer, Texas Tech Univ.; flexible MAV's
J. Li, Univ. of Nevada, LV.; high-order schemes
D. Rockwell, Lehigh Univ.; vortical flows

Publications

1. Gordnier, R. and Visbal, M., "Compact Difference Scheme Applied to Simulation of Low-Sweep Delta Wing Flows," *AIAA Journal*, Vol. 43, No. 8, Aug 2005.
2. Gursul, I., Gordnier, R. and Visbal, M., "Unsteady Aerodynamics of Non-Slender Delta Wings," *Progress in Aerospace Sciences*, 41, 2005.
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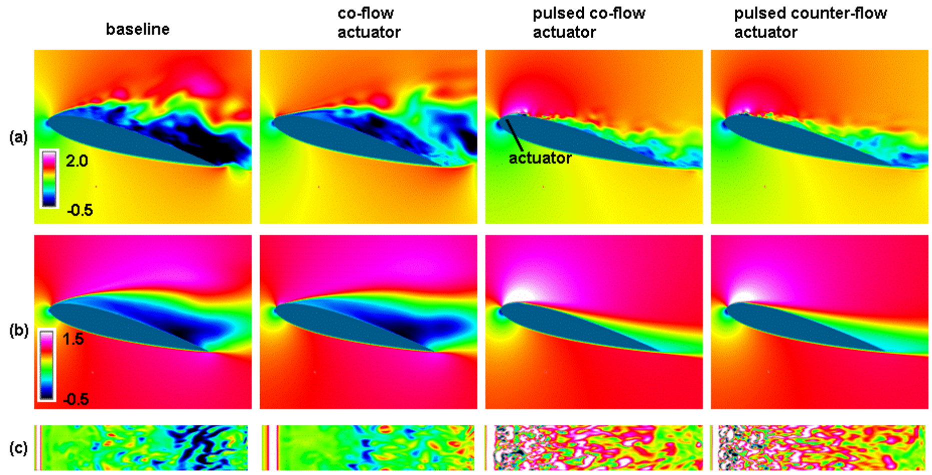

Figure 1. Effect of DBD actuator on stalled flow above a NACA 0015 wing section : (a) instantaneous and (b) mean streamwise velocity on vertical plane, and (c) spanwise vorticity on plane parallel to airfoil surface.

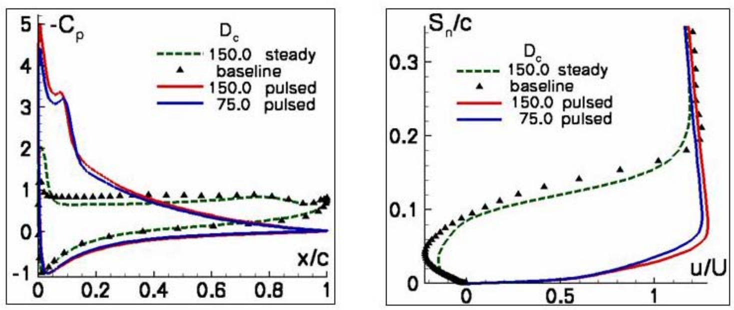

Figure 2. Effect of co-flow actuator on NACA 0015 airfoil flow: (a) mean surface pressure, and (b) time-averaged velocity profile near mid-chord.

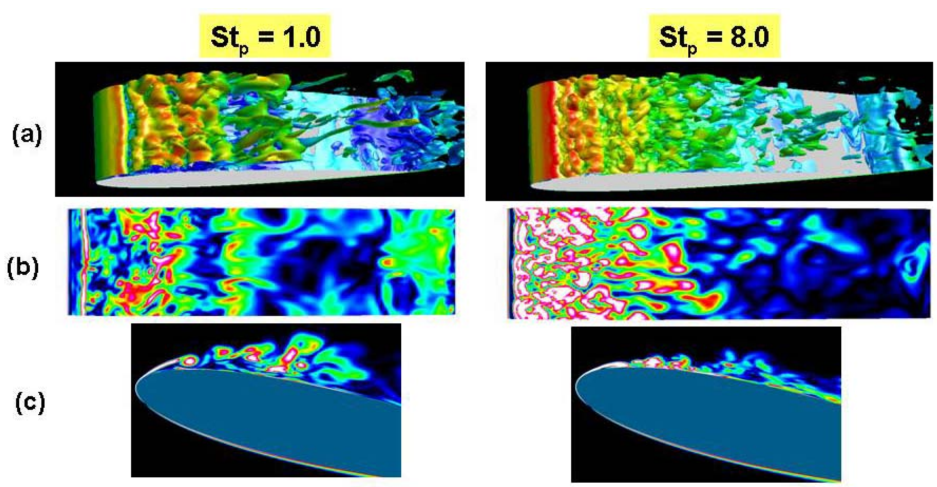

Figure 3. Effect of pulsing frequency of counter-flow DBD actuator on stalled flow above a NACA 0015 wing section: (a) iso-surface of vorticity magnitude; instantaneous vorticity magnitude on (b) a plane parallel to airfoil surface and (c) on vertical plane.

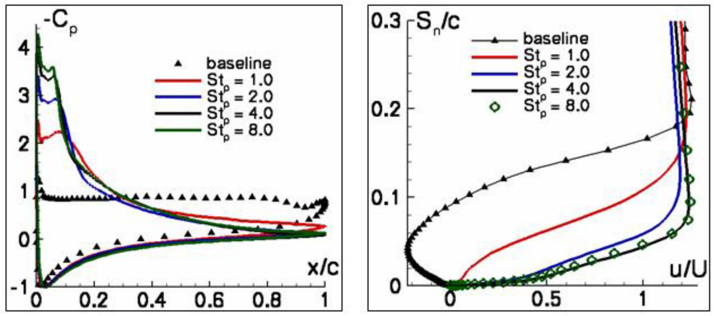

Figure 4. Effect of pulsing frequency of counter-flow DBD actuator on NACA 0015 airfoil flow: (a) mean surface pressure and (b) mean streamwise velocity profile near mid-chord.

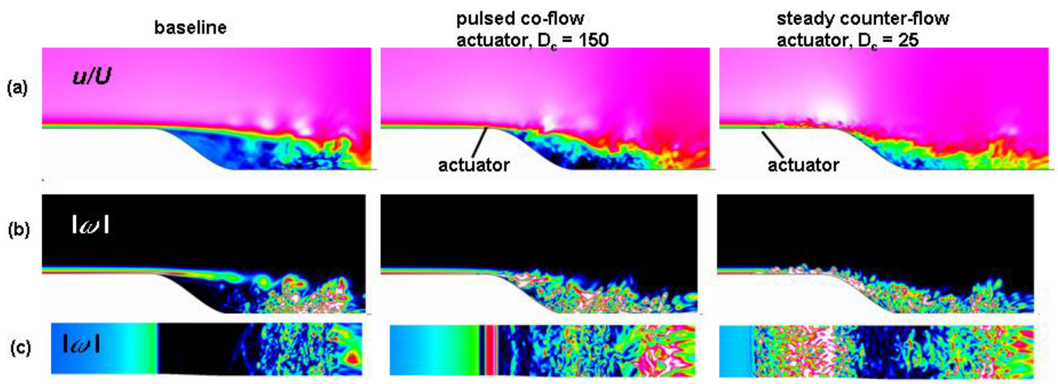

Figure 5. Effect of DBD actuator on instantaneous flow structure over a separation ramp: (a) streamwise velocity, and vorticity magnitude on (b) vertical plane and on (c) computational surface above the wall.

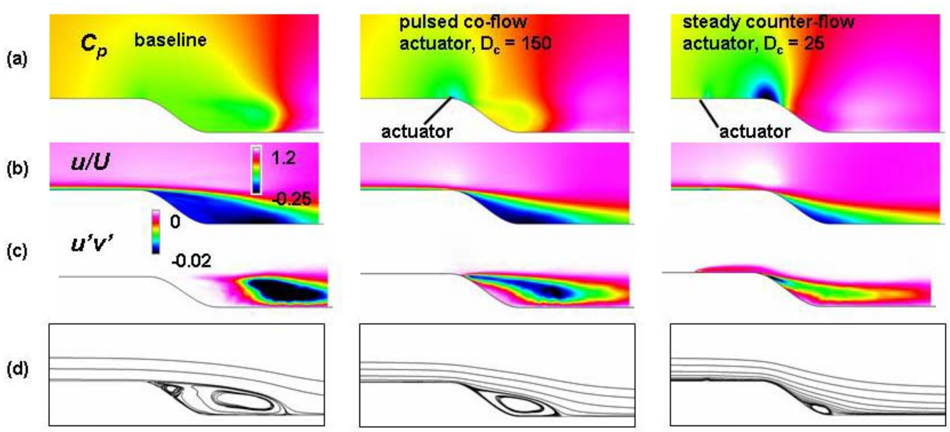

Figure 6. Effect of DBD actuator on time-averaged flow structure over a separation ramp: (a) static pressure, (b) streamwise velocity, (c) Reynolds stress, and (d) streamlines in separation region.